Consideration of fluid-structure interaction with the CEL approach for the FE-prediction of a blow-off pressure for an elastomeric seal

N Morrison, Y Gorash, R Hamilton
Weir Advanced Research Centre, Department of Mechanical and Aerospace Engineering, University of Strathclyde, UK

ABSTRACT

Assessment of leakage performance is a fundamental aspect in the design of elastomeric fluid seals. The key characteristic of the leakage performance is the blow-off pressure – when it is reached a seal no longer adequately performs its function. Realistic simulation of these phenomena under different conditions (amount of preload, pressure build-up rate, etc.) would facilitate improvement in the seal design methodology and would allow efficient optimisation of a seal design. For an accurate prediction of the blow-off pressure, Fluid-Structure Interaction (FSI) needs to be considered, since the geometrical disposition of the seal, its deformation and its contact conditions with respect to the main structure are adversely affected by the fluid flow and fluid pressure. In this study, the most advanced FSI technique currently available is employed for the numerical simulation – the Coupled Eulerian-Lagrangian (CEL) approach in ABAQUS [1]. This project leads the way for future work, to validate these results and determine the accuracy of the technique and its applications for more complex analyses.

1. INTRODUCTION

Accurate simulation of fluid structure interaction is a long running problem area in the world of fluid sealing. This report will attempt to address the difficulties associated with this type of problem by employing the CEL approach to facilitate computationally efficient, and accurate, prediction of the blow off pressure for a seal of typical geometry [2] and material properties.

The simulation work was completed using ABAQUS 6.14 as the CEL approach provided in this package allows for simultaneous computation of the fluid, and structure interaction effects, within one environment. This technique is a more advanced version of the arbitrary Eulerian-Lagrangian (AEL) approach which utilises adaptive re-meshing and transfers results taken at the solid boundary of a fluid problem, to the solid boundary of a solid problem, for each individual time step. This transferring of results leads to interpolation between the time steps which gives rise to an erroneous result. By using the CEL technique these errors can be eliminated, making it an attractive choice. However, it is not without its disadvantages; the improved accuracy over AEL comes with a substantial increase in solution time.

The geometry of the seal and the corresponding pressurisation model has been purposefully kept simple to increase computational efficiency and aid in the speed of analysis. In this paper we are interested in evaluating the performance of the technique and not the specific seal to which it is applied.

The main aim of this project was to conduct a sensitivity study for the compression of this typical seal geometry and therefore the shape of the seal will not be varied during the various analysis attempts. Parameters that have been investigated are the level of pre stretch in the circumferential direction and the level of compression of the seal in the radial direction. These different configurations were pressurised by a solid piston which pushed a fluid element. The corresponding leakage pressures for different compression levels have been obtained, and evaluated to determine if the CEL technique provides sensible results.

2. BACKGROUND

2.1. CEL Technique

More traditional FEA simulations use a purely Lagrangian mesh to monitor the deformation of solids from their reference position. This approach leads to inaccuracies, when applied to problems subject to large deformations, due to distortion of the shape of individual elements. As we expect the simulation considered in this project to undergo severe deformation of the fluid element, as it deforms to the shape of the solid seal, the Lagrangian mesh for this component is not appropriate.

The coupled Eulerian-Lagrangian approach is extremely useful for simulation of Multiphysics problems in which there is large deformation of the fluid-solid interface. This is due to the ability to track the position of the fluid elements when the solid boundary undergoes large deformations, without creating severe distortion of the mesh associated with the fluid domain. Having a fixed (Eulerian) mesh allows the fluid to move freely and make contact with solid boundaries and eliminates mesh distortion issues in the fluid. Further benefits of using an Eulerian mesh for the fluid domain is the capability for the creation and vanishing of the free boundary contacts in a realistic manner. Coupling this behaviour, with that of the seal finite elements, creates an accurate simulation of fluid structure interaction.

As the model is arranged with the Eulerian domain extending further than the seal (see figure 1) we can allow the fluid element to deform, pressurise the seal and simulate a leak past the sealing surface. Once a quantity of fluid has leaked past the seal, this approach allows for re-contact with the compression surface enabling prediction of the seal behaviour even after initial leakage occurs.

2.2. Limitations

The significant limitation of the CEL approach for fluid leakage problems is the time taken to complete the analysis. CEL is only available as a dynamic explicit analysis, and therefore, in the case of this study, the computation time for a three second simulation is of the order of 30 hours. For this reason, the mesh of the fluid element and the solid boundaries are kept reasonably coarse in an effort to reduce the solution time. Large computational time arises from the need to carry out the analysis in small, stable, time steps. The duration of the stable time increment is defined as the time taken for a pressure wave to propagate across any element in the analysis [3].

One proposed solution to reduce the solution time was to create all of the components, which are not of interest to the analysis, as analytical rigid surfaces. This appeared to reduce the computational intensity by a reasonable value, however, problems were faced when these surfaces were contacted by the fluid pressure. As one of the bases of this technique is small penetration of the fluid elements into the solid boundaries, gradually the fluid can leak through a thin surface. This effect highlights the limitations of the technique with respect to element type. Hence the analyses must be carried out with either standard solid or shell elements.

2.3. Application

Figure 1 shows the axisymmetric geometry of the pressurisation model which represents a cylindrical plug A, sealed by the seal C against the wall of a cylindrical borehole B. The interface between A and C is known as the "seat" which anchors the seal to the plug and prevents loss of the seal under pressurisation. In order to prevent leakage past the base of the seal, its inner diameter is smaller than that of the seat creating inward force on the seat, from the seal. Throughout the study of the seal, the level of compression applied by B will be varied.

3. MODELLING

3.1. Implicit Pre-strain

The initial implicit simulation of the seal pressurisation model was carried out in Solidworks and imported into ABAQUS as a .step file. An axisymmetric 1 degree segment of a seal with internal diameter 200mm was created and fixed in place by the plug and compression plate, see figure 1 (all components revolved about a single axis).

A – Plug

B – Compression plate (borehole)

C - Seal

Figure 1 – compression geometry

The purpose of this initial simulation was to compress the seal in the radial direction and stretch it in the circumferential direction. To simplify the analysis, all simulations were carried out at 10% strain in the circumferential direction. The value of compression was varied between 10mm and 20mm in 2.5mm increments to observe the consistency of the analysis technique in different configurations.

Creating an implicit model for this step reduces the computational time of the full analysis by approximately 4 hours. To use the results from this analysis, restart output requests were enabled in ABAQUS which allowed the displacements and reaction forces in the seal elements to be imported into an explicit analysis.

Setup is as follows:

3.1.1. Property

The first step of carrying out the implicit pre stretch analysis was to define the material properties for the seal and the compression components. These are specified below in section 3.3. The material properties assigned to the compression components are solely to avoid errors in the analysis. The solid runner and compression plate have been assigned rigid body constraints relative to a single reference point on each component making them non-deformable.

3.1.2. Assembly
The seal, runner and compression plate were instanced into the assembly and translated vertically relative to the global co-ordinate system in preparation for the boundary conditions. Translating the components vertically making the base of the seal 200mm above the origin allows boundary conditions to be defined about the origin.

3.1.3. Step
One step was created with duration 1 second, to allow for simultaneous compression and stretch of seal. As the analysis considered in this report contains deformations which produce large values of strain, non-linear geometry controls were turned on (NLGEOM).

A restart output request was requested at this point enabling the analysis to be imported into explicit.

3.1.4. Interaction
The surface contacts are important in this analysis as, for this type of seal geometry; the contact surface will be affected by friction as it approaches leakage.
Both the seat surface and the sealing surface were assigned a standard surface to surface contact with an interaction property defining a friction coefficient of 0.3 [4].

Constraints were applied to compression components defining them as rigid bodies.

3.1.5. Load
Loading was applied thorough typical displacement boundary conditions. Encastre was used on the reference point of the runner component (Lower compression surface) and a simple displacement boundary condition was applied to the reference point of the upper compression surface.

The rubber seal geometry was constrained to have no movement on the “cut plane” on the rear side cross section. It is important that this boundary condition only applies to one direction i.e. wall normal, this is achieved by placing a datum co-ordinate system on the face of the seal and specifying no movement in the z direction (datum CSYS 1).

The movement of the opposite face of the rubber seal (the cut plane at 0.9deg) was defined by a rotational displacement boundary condition. In order to achieve the desired sweep through 0.1 degrees, a second datum co-ordinate system was defined at the origin (origin placed on the axis of rotation). This is a cylindrical CSYS allowing a displacement to be specified as an arc. The purpose of this boundary condition was to pre-stretch the seal and bring the face of the seal flush with the cut faces of the compression parts.

3.1.6. Mesh
The three parts here are meshed using standard linear hexagonal elements with reduced integration (C3D8R) with additional enhanced hour-glassing controls.

Typically the elements used to analyse near incompressible hyper-elastic materials are hybrid formulation, however, this formulation is not compatible with explicit import therefore they cannot be used.

Additional input is required to change the type of the elements to explicit formulation, as they will be imported into an explicit analysis; this improves the stability of the elements in the explicit analysis.

3.1.7. Keyword changes

The above mentioned problem restricting the use of hybrid formulation elements causes an error when attempting to run the job. This is due to the standard element formulation not being the most suitable for near-incompressible materials. Keywords must be edited, adding a waiver for the error message and downgrading it to a warning message in the output file. The text than needs to be added is inserted in to the keyword editor, after the third line in the "Step" section, is:

*DIAGNOSTICS, NONHYBRID=WARNING

This is not recommended by ABAQUS documentation; however, it is justified in this case as validation studies showed that an analysis with hybrid formulation elements produced the same outputs in this case.

3.2. Dynamic Explicit Loading

D – Eulerian domain

E – Initial fluid position

F – Piston

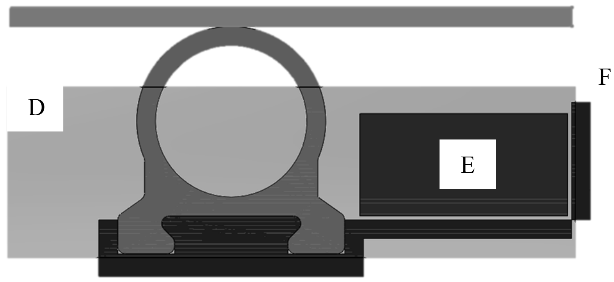


Figure 2 – geometry with fluid element

Figure 2 shows the full arrangement of the seal compression model. The CEL technique requires an Eulerian domain (D, transparent body), overlapping all solid boundaries which fluid will come into contact with, to be meshed and constrained to specify the limits of translation of the fluid elements. A smaller solid domain - E, within the Eulerian part is used to define the initial position of fluid elements; this is achieved using the volume fraction tool and a material assignment predefined field. CEL allows for free movement of the fluid elements within the Eulerian domain, tracking the surface of the fluid as well as the volume of fluid contained in each individual element of the domain (Eulerian volume fraction void). The particulars of the fluid structure interaction are then defined by an "all with self, contact."

Fluid pressure is applied to the seal by moving a solid piston – F, towards the seal, compressing the fluid element. All solid bodies within the model, excluding the seal, are modelled as rigid bodies in an effort to reduce computational cost.

The model for dynamic explicit pressurisation is copied from implicit pre stretch with changes as detailed below:

3.2.1. Property
Material properties are defined as specified in section 3.3 for the water, and the properties of steel and rubber are identical to the last analysis.

3.2.2. Assembly
Additional components needed for the pressurisation step are: the piston, the Eulerian domain and the initial position component. These parts are instanced in to the assembly and translated to their desired position.

The compression plate component is also translated to where it moved to in the last step of the previous analysis. This is its desired positon for the duration of this analysis.

The part which defines the initial position of the water is not included in the analysis but is necessary to create the discreet field used to assign material. The purpose of the Eulerian component is purely to define the mesh for the region in which the water can flow freely; this component will not be visible during analysis.

Note: Type of part must be changed from "Solid deformable" to "Eulerian" in order to create a CEL model.

3.2.3. Step
In order to change the definition of the step in the copied analysis, the static step was replaced with a dynamic explicit step. The replacement of this step allows all boundary conditions and contact definitions to be redefined automatically without any user input, making this a valuable time saving operation.

The new analysis step is defined with nonlinear geometry controls on to be consistent with previous import analyses. This step has duration 3 seconds. The time frame was chosen to reduce the dynamic effects caused by the momentum of the fluid impacting the solid seal geometry.

3.2.4. Interaction
The previous contact definitions between the seal and compression components have automatically been converted into explicit format so will remain unchanged from the copied analysis.

A new contact must be defined to specify the properties of the contact between the fluid elements and the structures which they are in contact with. This "All with self" contact is defined with a coefficient of friction equal to 0.1 to allow the fluid to move freely inside the pressurisation model.

In order to define the material assignment of the fluid elements, a discreet field must be defined at this stage. Discreet fields are created using the volume fraction tool.

3.2.5. Load
The previous boundary conditions for the seal geometry and compression components have been converted into explicit format so will remain unchanged from the copied analysis.

New boundary conditions defined at this stage are the conditions which prevent the fluid elements from leaking out of the Eulerian component in the wall normal direction. This is achieved by placing a datum CSYS on the surface of the Eulerian and defining no displacement in the z direction. The same process is repeated on the opposite face at 0.1 degrees rotation.

The compression plate boundary condition is modified in this step. Its converted boundary condition contains the compression movement, which is not desired in this analysis. This is modified to be stationary for the duration of the analysis in its new position defined in the assembly step.

A predefined field is applied to the seal to specify its initial configuration in this analysis transferring the displacements from the implicit analysis. A second predefined field is defined to assign material (water) to the initial condition component.

3.2.6. Mesh
All of the parts used in the initial stretch analysis maintain their formulation in this analysis; the piston part is also meshed using C3D8R elements. The initial position part does not require a mesh as it will be suppressed for the analysis.

EC3D8R elements are assigned to the Eulerian component. Note that the type of the part must be changed to Eulerian before these elements can be assigned.

3.2.7. Job
Job submission is carried out using the regular procedure to submit jobs on ABAQUS. Due to the computationally intensive nature of this simulation, parallelisation was employed to aid in the speed of analysis. Using the ARCHIE-WeSt high performance computing facility it was possible to assign 16 processor cores to each analysis, reducing the runtime (by 75%) to approximately 20 hours.

3.3. Material Properties

3.3.1. Steel
Steel was assigned to the solid compression components and the piston, primarily to assign mass, as they have rigid body constraints and therefore do not deform. These properties are not essential to the analysis but are required to run the simulation.

Properties:
Density – 7800 kg/m^3
Young's modulus – 210 GPa
Poisson's ratio – 0.3

3.3.2. Water
The definition of the material properties for water is taken from a Simuleon tutorial for a model of a boat floating [5]. These properties are also the ABAQUS recommended setup for water using the equation of state Up-Us and are input in SI units.

Properties:
Equation of state – Up-Us, c0 = 1483 m/s, s = 0, Gamma0 = 0
Density – 1000 kg/m^3
Viscosity – 0.001 Pa*s

3.3.3. Rubber
The Ogden material model was used for the hyper-elastic seal material. The corresponding material parameters have been identified for SI unit system (Pa, m, s)

using internal ABAQUS evaluation procedure applied to a classical Treloar's stress-stain curves set for a vulcanised rubber [6] – refer to a parallel paper number 25 for details [7].

4. RESULTS

Simulations converged successfully for a range of results as shown in table 1 and figure 3 which show the blow off pressures for different compression levels. These values were collected in the ABAQUS post processor using the SVAG pressure measure, which allows users to view the development of pressure over time and the distribution of pressures within the model. These values are the maximum pressures achieved by the seal at the point of total failure. All results were collected with a 10% initial circumferential strain.

Table 1: Failure Pressures

Compression level	Blow off pressure
10 mm	15 kPa
12.5 mm	21 kPa
15 mm	47 kPa
17.5 mm	62 kPa
20 mm	66 kPa

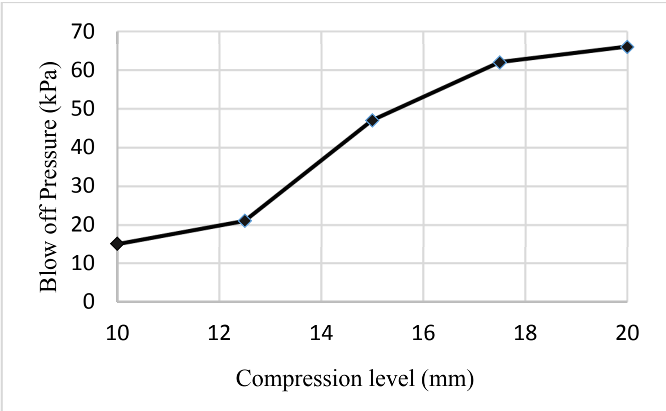


Figure 3: graph of Compression level vs Blow off pressure

The change in the rate of increase in blow off pressure between compression levels, as seen in figure 3, shows that the seal in question has a maximum effective compression level for the given pre strain which can be approximated to be 20mm from this graph. At this maximum effective compression level additional compression yields marginal gains on sealing pressure. The levelling off of the graph is an expected result and an early indicator that the results are consistent and realistic.

No significant validation of this seal geometry has been carried out as part of this project therefore the order of magnitude of the results cannot be commented on in detail.

However, analysis of individual results shows that the failure mechanisms for different compression levels vary.

4.1. 10mm Compression

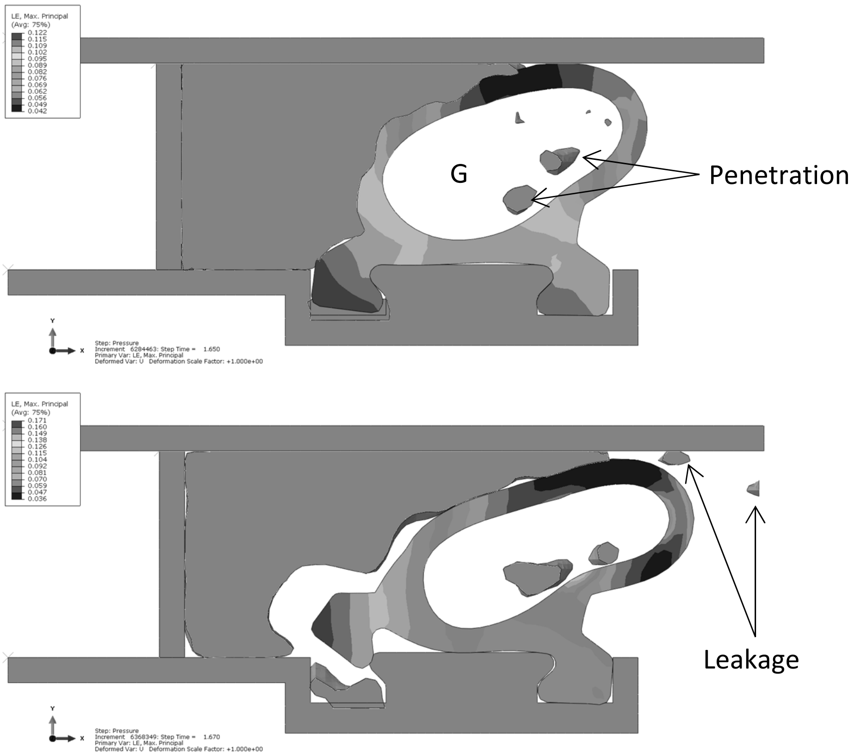


Figure 4: 10mm: Top - seal under pressure, bottom - seal failure

The starting point for the analysis is at 10mm seal compression and 10% circumferential strain. This provides a reasonable contact gap to seal the fluid and prevent leakage at low pressures. As can be seen in figure 4-top, the seal undergoes sliding deformation at the contact gap when fluid pressure is applied, this causes the contact patch to reduce and, as a consequence of this, the seal begins to leak at approximately 10kPa. Leakage is identified in ABAQUS post processing using EVF void to visualise the position of the fluid during the analysis. Slight fluid penetration is observed in the seal cavity G which is not classed as leakage and is caused by slight misalignment of the seal and Eulerian domain.

This can be called an elastic leak as the seal has the ability to recover when the pressure is relieved, provided that the pressure does not reach that required for total failure.

When the seal reaches total failure pressure (15 kPa) it is pulled out from the anchor, in this case only one anchor point was lost but the seal cannot recover to its initial sealing pressure.

4.2. 12.5mm Compression

Figure 5: 12.5mm: Top - seal under pressure, bottom - seal failure

In order to obtain an accurate picture of how the seal behaves at different compression levels, an increment of 2.5mm was chosen.

The seal behaves in a similar manner in this analysis as in the 10mm compression analysis. Under loading the seal slides to deform to its state in figure 5-top, before an elastic leak occurs at approximately 15kPa. Leakage continues until the pressure climbs to 21kPa, at which seal suffers total failure. Due to the higher sealing pressure the loss of the seal is much more violent causing both anchor points to be pulled out from the seat.

4.3. 15mm Compression

Figure 6: 15mm: Top - seal under pressure, bottom – seal failure

15mm compression follows a similar path to the previous analysis by deforming by sliding before total failure. However, in this case the analysis results indicate that there is no elastic leak before failure. When the pressure reaches its maximum (47 kPa) - the upper wall of the seal cavity, shown in figure 6-top, collapses into the cavity causing the seal to separate from the contact gap. This is an interesting failure mechanism and suggests that leakage will not always occur before failure.

4.4. 17.5mm Compression

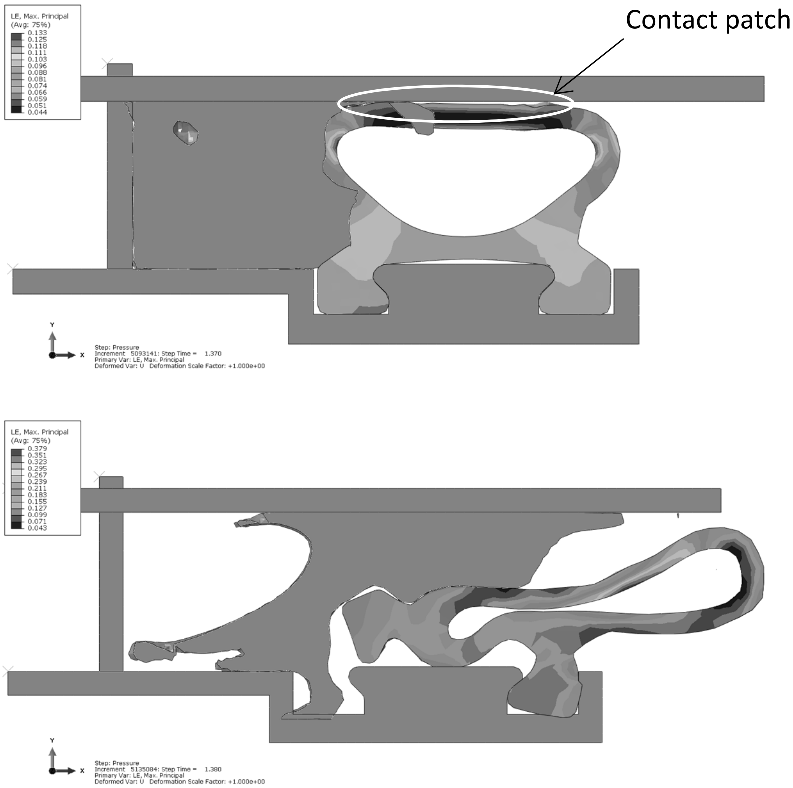


Figure 7: 17.5mm: Top - seal under pressure, bottom - seal failure

The results from 17.5mm compression differ slightly from previous analyses, at this level of compression the seal has a large contact patch and does not slide before leakage due to the high frictional resistance. In this configuration elastic leakage begins at approximately 39kPa and continues for a longer time up to the failure pressure of 62 kPa. When failure does occur it is less dynamic than previous analyses losing only one anchor point.

4.5. 20mm Compression

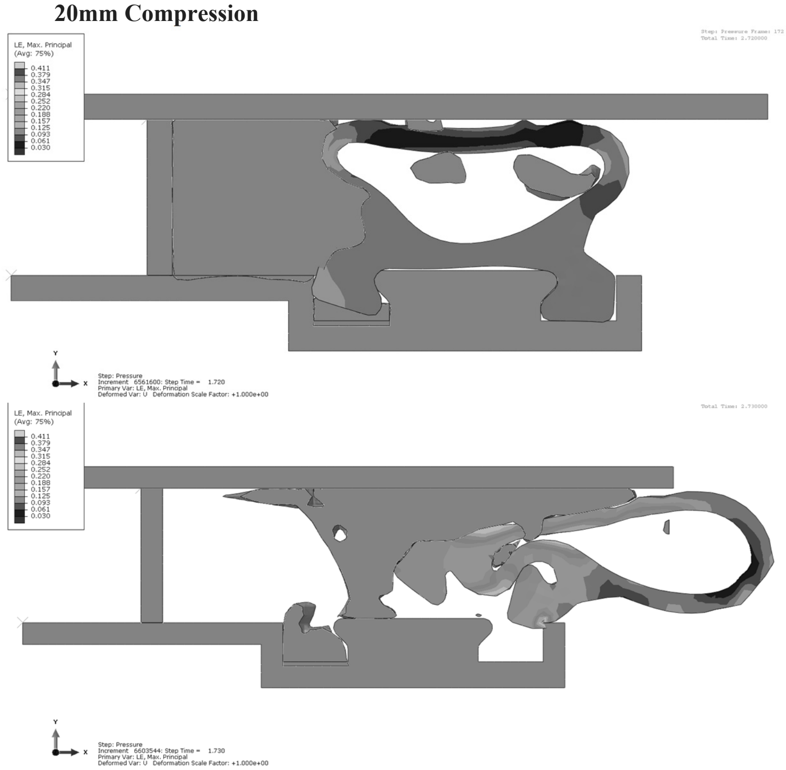
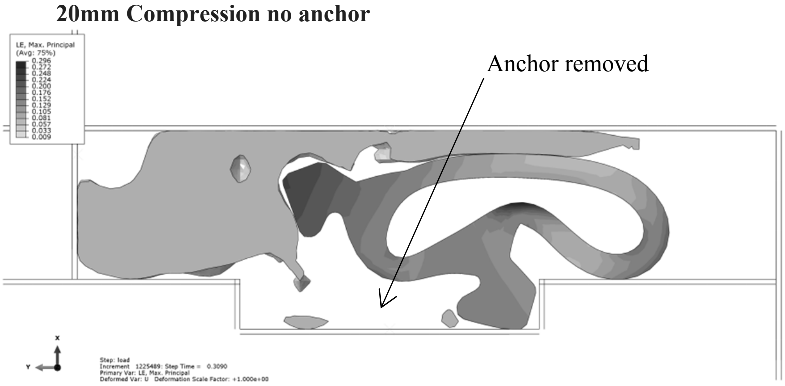


Figure 8: 20mm: Top - seal under pressure, bottom - seal failure

The final analysis in this range is carried out at 20mm compression and produces similar results to the analyses carried out at 17.5mm. In this case the seal is pressurised up approximately 41kPa before elastic leakage occurs, and the seal undergoes a substantial elastic leak before total failure (66kPa).

4.6. 20mm Compression no anchor



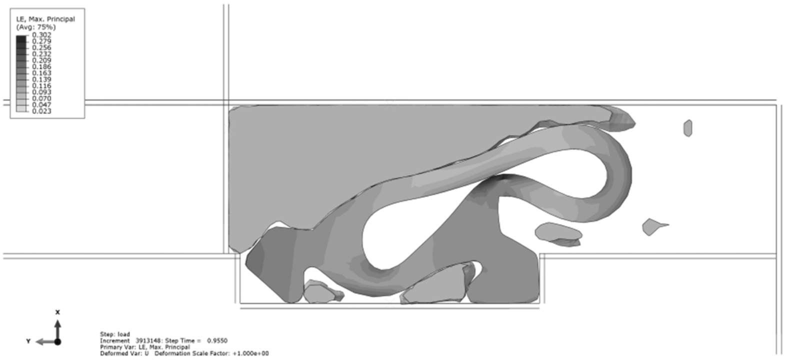


Figure 9: 20mm: Top - 1st leak, bottom - 2nd leak

To further investigate failure mechanisms of different seal compression configurations, a simulation was run at 20mm compression with no anchor at the seat of the seal. In the initial stage of the simulation the seal compresses to a similar shape as in the previous 20mm anchored analysis (4.5. 20mm compression). However figure 9 top shows significantly different behaviour from 4.5 when leakage occurs, the seal suffers sliding deformation under pressurisation until contact is lost and the seal rotates opening the leakage gap further. The leakage causes a drop in pressure allowing the seal to move freely back to its original position and re-seal. As a result of this, the seal is able to withstand close to its original sealing pressure before leaking for a second time.

This behaviour is significantly different to that of all previous simulations and illustrates the range of failure mechanisms that the CEL technique is capable of simulating.

5. DISCUSSION AND CONCLUSION

The primary conclusion to be drawn from the results is that leakage behaviour is not consistent. For different compression levels, the failure mechanisms can be substantially different making prediction of the failure mechanism before analysis extremely difficult. However, this analysis technique has provided very promising results and may be the best technique for accurate prediction of blow off pressure and seal behaviour. ABAQUS appears to be a very capable and powerful tool for Multiphysics analysis and this project will continue to utilise this simulation package to further investigate leakage behaviour and develop the accuracy of the results.

Future work may focus on applying this technique to a problem which can be tested in a physical environment alongside a finite element environment. This would provide the opportunity to compare analysis results with laboratory results to solidify the validity of the technique.

The ability to accurately and reliably predict the seal failure mechanisms and maximum pressure of seals will change the way seal design is approached. For example, the failures observed in these analyses would suggest that seal retention rings either side of the seal would prevent extrusion of the seal though the compression gap and increase the safe sealing pressure.

6. ACKNOWLEDGEMENTS

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